NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 4012

FATIGUE-CRACK PROPAGATION AND RESIDUAL STATIC STRENGTH OF BUILT-UP STRUCTURES

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SUMMARY

Fatigue tests were conducted on box beams and tension panels in order to study some of the factors affecting fatigue-crack propagation. The box beams had essentially the same configuration except for the mode of connecting stringers to the tension cover. The beams with bonded stringers had the lowest rate of crack growth, and beams with riveted and integral stiffeners had successively higher rates of crack growth. Crack growth was slower in beams with close rivet spacing than in beams with greater rivet spacing. The tension panels were all of the same general configuration except that the proportions of cross-sectional areas of skin, stringers, and flanges were varied. Panels with heavy stringers and thin skin had lower rates of crack growth than did panels with heavy skin and light stringers.

Static tests were performed on box beams, on tension panels, and on two types of wings, all of which contained fatigue cracks. The comparison of results with predictions made by a simple theory indicates that test results were affected by a redistribution of loads among the various remaining elements and by whether cracks terminated at rivet holes.

INTRODUCTION

During the past several years the idea of "fail-safe" design has become a very popular topic for discussion among aircraft structural designers. Although the conditions for calling a given design fail-safe have not been clearly defined, almost all engineers concerned agree on several general conditions. First, the progress of a fatigue crack through a structure must be reasonably slow, preferably in a readily inspectable location. Second, the structure containing a crack must retain enough static strength to withstand some specified load.

The means for accomplishing these ends involve such factors as the selection of materials with satisfactory crack propagation and static notch-strength properties, the arrangement of material to inhibit crack growth, the provision of multiple load paths, and others. The purpose of the present paper is to review current research which deals with the systematic study of some of these factors and their application to the design of structures used in wings.

CRACK PROPAGATION

Box Beams

One phase of the study of crack propagation involves fatigue tests of box beams such as those shown in figure 1. Two general configurations were tested. For the first configuration the tension cover had integral stiffeners and was machined from a plate. For the other configuration the stringers and skin were either bonded or riveted. The webs and compression covers on all beams were of identical built-up construction for simplicity in construction and analysis. All beams were 20 inches wide and 8 feet long. Identical beams were constructed in each of the aluminum alloys, 2024 and 7075. The beams were loaded as shown in figure 1 to produce tensile stresses of 13 ± 6.5 ksi in the carry-through bay. An oblong hole was made in the center of the carry-through bay to initiate the crack at that point. Cracks generally grew symmetrically across the chord. Although some of the data have been published previously (ref. 1), representative results are given in figure 2.

In figure 2 the percentage of the tension area lost by fatigue cracking is plotted as a function of the number of cycles of load applied after crack initiation. The curves are for beams with integral, riveted, and bonded covers. The material in each case was 7075 aluminum alloy. The results for 2024 aluminum-alloy beams are not shown, but the same general observations apply except that crack growth is appreciably slower in beams made of 2024 aluminum alloy.

As indicated by the curves, the cracks grew least rapidly in beams with bonded covers. The crack growth was confined to the skin and progressed at a reasonable rate, probably controlled by support from the stringers. Measurements of stringer stresses taken at intervals during the test indicated that these stresses increased more slowly than stresses in beams with other types of connections, probably because of the fact that the bond between the skin and stringers peeled back as the crack grew across the beam. Since there were no rivet holes in the stringers, no stress raisers were present, and no stringers failed before the crack had grown completely through the skin.

In riveted covers the stringers were somewhat more vulnerable to failure because stringer stresses increased more rapidly and stress raisers due to rivet holes were present. The loss of stringers in the case of riveted beams contributes to the more rapid loss of tension material. In the case of the integrally stiffened covers the cracks grew at the fastest rate because no natural barriers to crack growth were present.

These observations indicate that crack propagation is very much a function of the effectiveness of connections between the sheet and stringers. An extension of this work to beams in which the rivet pitch was varied was therefore undertaken, and some of the results of this work are shown in figure 3.

In figure 3 the curves from figure 2 are replotted as solid lines. New curves for beams with rivet pitches of one-half and of twice the rivet pitch used in the previous beam are shown by dotted lines. The symbols represent the stage of the test when one or more stringers had completely failed. Crack growth was slower in beams with a rivet pitch of 3/4 inch than in those with a rivet pitch of $1\frac{1}{2}$ inches and was much slower than in beams with a rivet pitch of 3 inches. The stress measurements previously mentioned indicated that stresses in stringers straddling cracks increased more rapidly in beams with a rivet pitch of 3/4 inch than in other beams with riveted stringers. This increase in stresses had two effects: a slow rate of crack propagation in the sheet as indicated by the low initial slope of this curve, and increased probability of stringer failure as indicated by the fact that in this beam two stringers failed after only about 8 percent of the structure had been lost by skin cracking. On the other hand, in beams with a rivet pitch of 3 inches, the stringer stress increased more slowly and indicated that less support was given to the sheet; consequently, crack growth was very rapid in the skin. The results of these tests show that the closer the rivet pitch, the better the resistance to crack propagation. Fabrication limitations prevent decreasing the rivet pitch further. Integral construction, which might appear the same as rivets with a zero pitch, displays rapid crack growth. The reason appears to be that in integral construction only one crack needs to be started, and then that crack grows completely through the panel.

Tension Panels

Another phase of the investigation of crack propagation involves tension tests of stiffened panels. Some of the results are shown in figure 4. The panels tested were 30 inches wide and were composed of a skin, four stringers, and two flanges. The parameters varied were the percentages of the areas of skin, stringers, and flanges as indicated by values listed in the figure. Two of the configurations had 40 percent of the area in the skin, and one configuration had 80 percent of the area in the skin. Many current aircraft have proportions within this range. Repeated tension loads were applied to produce nominal stresses of 14 ± 4.7 ksi. Fatigue cracks were initiated at cutouts with the shapes indicated in figure 4. Although only a few results are available, preliminary discussions are of interest.

The heavier stringers in panels with 40 percent of the area in the skin appear to have controlled the rate of crack growth more effectively than in the panels with 80 percent of the area in the skin. The result is an appreciably lower rate of crack propagation in panels with lighter gage skin. One configuration had a 5-inch-square cutout which was the width of one skin panel. This cutout removed approximately 7 percent of the original net section, and the beginning of the curve for this specimen is plotted at that value. In this case the growth of fatigue cracks was very slow in the initial stages of the test and illustrated the beneficial effect of framing members adjacent to cutouts.

RESIDUAL STATIC STRENGTH

The rest of this paper deals with the study of residual static strength in the specimens just described. The results which are preliminary in nature are discussed in order to indicate trends. These results are then compared with results of a simple analysis. Static tests of Convair 240 (designated herein as CV-240) and C-46 wings containing fatigue cracks are also discussed.

Box Beams

In figure 5 the ordinate represents the ultimate load producing static failure of beams with cracks expressed as a percent of the load calculated to produce failure of the tension covers in uncracked beams. The abscissa represents the length of the fatigue crack in the cover skin. The symbols represent the results of static tests of box beams which were made of 7075 aluminum alloy and which were identical except for the fastenings between the skin and stringers. The symbols represent either bonded covers or riveted covers as shown in figure 5. The dotted line represents the strength of the beam having a skin crack only, with no allowance made for stress concentration K due to the crack. The solid lines represent predictions made by calculations of the static strength of a specimen containing a fatigue crack in the skin only. The basis of this method is to compute a stress-concentration factor K_u for the sheet by the method outlined in reference 2. The residual static strength of a sheet containing a crack was added to the static strength of structural members such as stringers and flanges to produce the values for the upper curve. Each of the other curves was computed in a similar way except that one or more stringers were assumed failed. Each test point is connected by a vertical line to the curve appropriate for the number of stringers failed in the specimen represented.

When the crudeness of the method used is considered, the agreement between predicted strength and actual strength of riveted beams is good. The beams with a rivet pitch of 3/4 inch fall farthest below the predicted curves, probably because of the higher stresses carried by stringers. Evidently the distribution of loads among the remaining members in the structure must be taken into account in order to improve the predictions. The strengths of beams with bonded covers are higher than the respective predicted strengths while other strengths are lower than predicted. No reason for this behavior has been found. One point fell above the dotted line which represents loss of strength equal to loss of area. This high strength was caused by the fact that the actual material strength was higher than the specification values used in computations. Adjustment of the computation for actual material properties would affect all the results.

Tension Panels

Figure 6 gives results similar to those in figure 5 for static tests of the tension panels with 80 percent of the area in the skin. In this case the data were somewhat higher than predictions (shown by solid lines in the figure) made by the method previously used. The reason appears to be that in these panels the fatigue cracks ended at rivet holes. The computation of the stress-concentration factor should, therefore, allow for a radius of curvature ρ equal to the radius of the rivet instead of the effective radius at the root of a crack. Calculations based on this assumption are indicated by the dashed lines, and the test results fall below the predictions as before.

CV-240 Wings

Some CV-240 outer wing panels were subjected to repeated loading in order that crack growth might be studied, and then static tests were performed in order that the residual static strength might be determined. Figure 7 presents the results of three static tests of CV-240 wings containing fatigue cracks. The plot of figure 7 is similar to the plots of figures 5 and 6 except that the abscissa is the tension cross-sectional area failed expressed as a percentage of the total tension cross-sectional area. The dotted line represents reduction in static strength in the same proportion as the reduction in area. These wings were constructed of 7075 aluminum alloy, and the structure was somewhat more complex than that of the box beams discussed previously. As before, the stress concentration was computed for the skin only. Also, since cracks terminated at rivet holes or grew to rivet holes at an early stage of the static test, the rivet radius was used in the calculations. The cracks in these wings originated in the rear spar caps and then grew across the chord. The calculation was, therefore, for a sheet with a notch on one side only. The test results fell slightly below the prediction as before.

C-46 Wings

The fatigue tests of C-46 wings have been discussed in references 3 and 4. Thirteen wings were static tested after various amounts of the tension material were failed in fatigue tests. The results of the static tests have been presented in reference 4.

The results are also shown in figure 8 in the same type of plot as was used in figure 7. The predicted curve was computed on the assumption that the skin was continuous across the chord. The rivet radius was used in the calculation for the same reason as before. In spite of the fact that a wide variety of structural members failed during the fatigue tests on these specimens, the predicted strengths fell in a very narrow band which is represented in the figure as a single line. The discrepancy between results and predictions was somewhat greater than in the previous cases. This discrepancy was to be expected as a result of the much more complicated structure in the C-46 wings. Obviously, the redistribution of loads in this structure will have to be considered before more accurate predictions can be made.

The apparent large loss of strength with small cracks applies only to the tension surface. In compression-critical wings, such as the C-46 and CV-240, the loss in wing strength is very small until large cracks are present.

CONCLUDING REMARKS

Crack-propagation and static-strength tests in several types of built-up specimens and full-scale wings have been reviewed. The results, to date, indicate that the rate of crack propagation is influenced strongly by the mode of connecting the skin to stringers and by the proportions of areas of the skin and stringers. The analysis of residual static strength of complex structures indicates the feasibility of applying simple methods, but the results are subject to questions regarding the redistribution of loads, interactions between various members, and such seemingly trivial considerations as whether or not a crack terminates at a rivet. Much work remains to be done on these problems. Other configurations designed to improve both the rate of crack propagation and residual static strength should be investigated.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., March 6, 1957.

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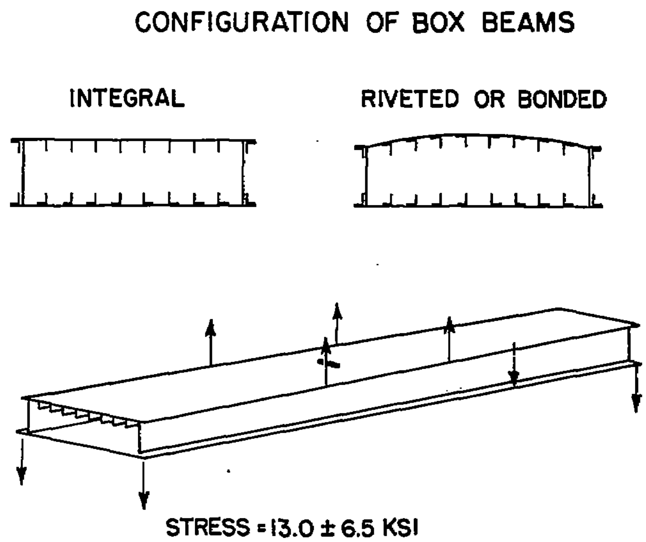

Figure 1

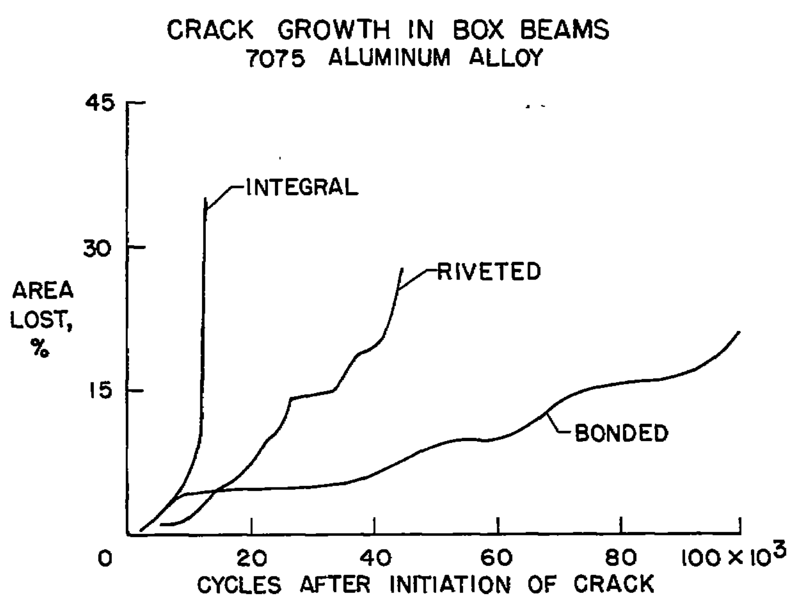

Figure 2

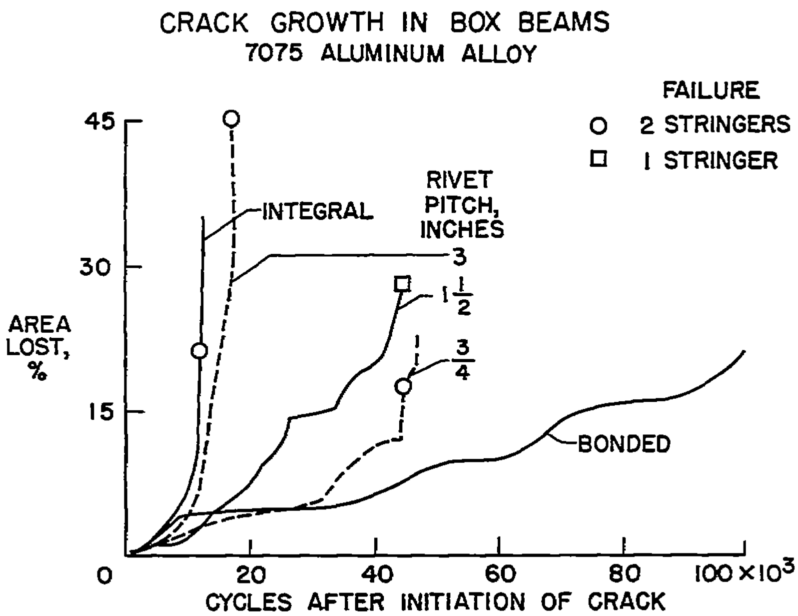

Figure 3

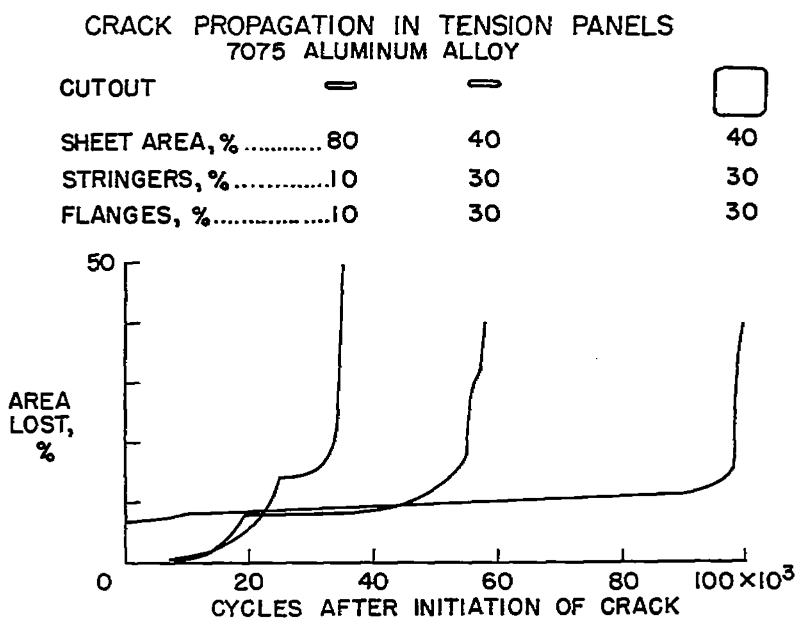

Figure 4

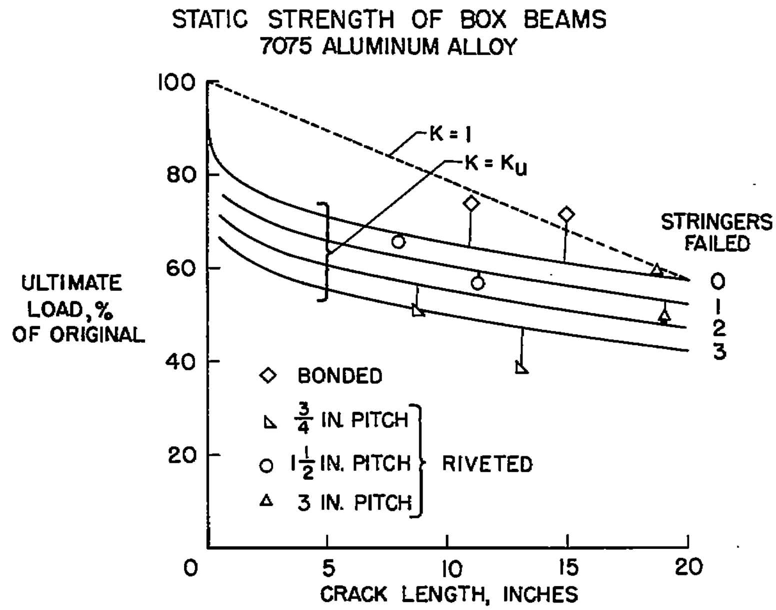

Figure 5

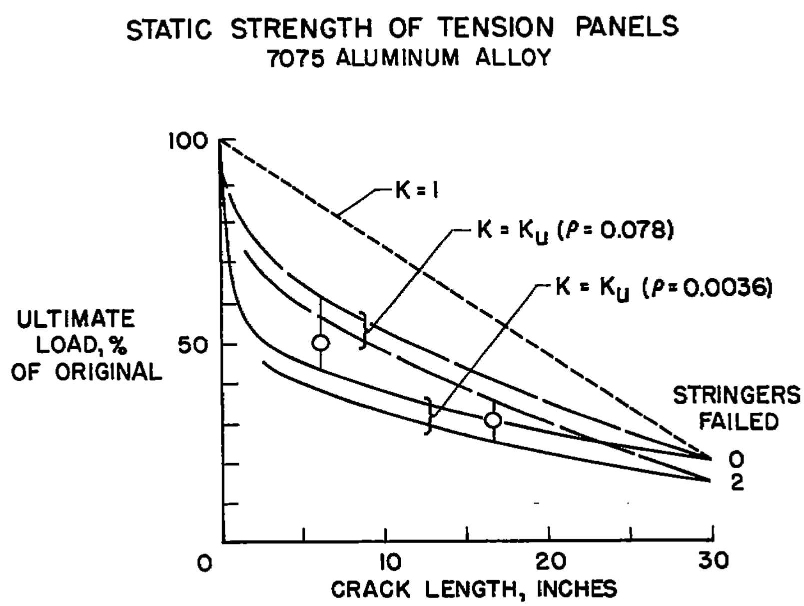

Figure 6

STATIC STRENGTH OF CV-240 WINGS
7075 ALUMINUM ALLOY

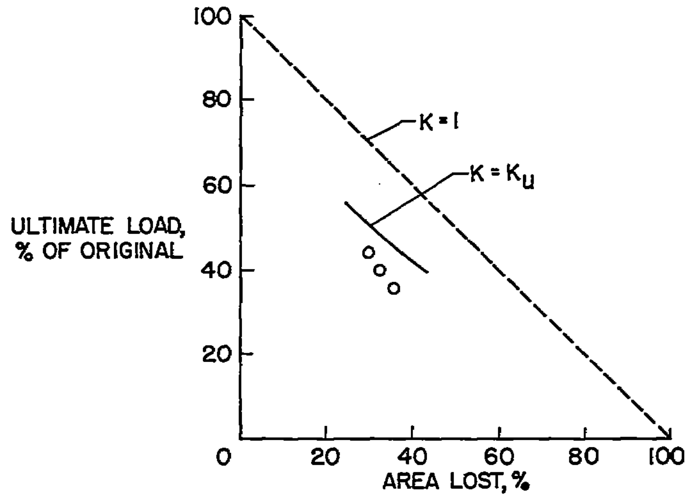

Figure 7

STATIC STRENGTH OF C-46 WINGS
2024 CLAD ALUMINUM ALLOY

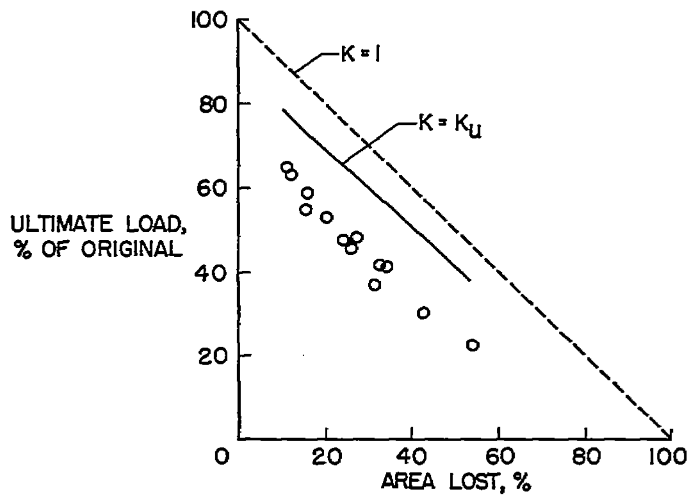

Figure 8

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